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On the Interaction Between Cosmic Rays and Dark Matter Molecular Clouds - II. The Age Distribution of Cosmic Ray Electrons.

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ABSTRACT
We explore further the proposal in paper I of this series that the confinement time of cosmic ray nuclei in the Milky Way is determined by their interaction with dark matter molecular clouds rather than by their escape from the halo, as is assumed in conventional models of cosmic ray propagation. The same proposal can be made for cosmic ray electrons. This proposal leads to a specific age distribution for the electrons which is in agreement with Tang's (1984) observations of the electron spectrum at high energies but not with Nishimura et al's (1980) earlier data, which lead to a flatter spectrum. However, the simplest leaky box and diffusion models disagree with both sets of data so that our trapping model is supported if Tang's data are correct.

Key words: ISM – clouds – cosmic rays – dark matter

1 INTRODUCTION

This is the second paper of a series devoted to the interaction between cosmic rays and the molecular clouds which have been proposed as the source of the dark matter in the Milky Way (Pfenniger Combes & Martinet 1994, De Paolis et al 1995, Gerhard & Silk 1996). In paper I (Sciama 1999) it was pointed out that, if cosmic rays can penetrate these clouds, then a number of observable effects would arise, and that some of these effects may have already been observed. In particular it was noted that a cosmic ray nucleus such as carbon which entered a cloud would be completely fragmented by interacting with the molecular hydrogen of column density ~ 50 gm cm^{-2} characteristic of a cloud in the favoured model. The resulting mean survival time for a relativistic nucleus propagating in the interstellar medium would be of order 10^{15} secs. Since this is of the same order as the observed confinement time for relativistic radioactive cosmic ray nuclei such as Be^{10} and Al^{26} (Simpson & Connell 1998, Webber & Soutoul 1998), it was proposed in I that trapping by dark matter molecular clouds, rather than leakage from the boundaries of the halo (as usually assumed), is the mechanism determining the escape of cosmic ray nuclei from the interstellar medium.

This proposal is further elaborated here and extended to cosmic ray electrons. These particles lose most of their

energy when they enter a cloud, and so are then effectively lost to the propagating electron population, since the observed spectrum of these electrons declines rather steeply with energy. The main aim of this paper is to investigate whether this trapping model for the electrons agrees better with observation than the conventional models in which the electrons, like the nuclei, escape from the boundaries of the halo.

The next section is devoted to a discussion of some of the differences between the standard propagation models and our trapping model. This discussion brings out the importance of the energy dependence of various parameters in the different models. Sections 3 and 4, respectively, are devoted to this dependence for the path length of cosmic rays and to the surviving fractions of radioactive species. Section 5 is concerned with the numerical value of the mean confinement time t_e of cosmic ray electrons, and section 6 discusses their age distribution and the energy dependence of t_e. Finally section 7 contains our conclusions.

2 COSMIC RAY DIFFUSION IN THE PRESENCE OF TRAPPING

Conventional discussions of cosmic ray propagation are mainly based on either the leaky box model or on diffusion models (Ginzburg & Syrovatskii 1964, Daniel & Stephens 1975, Berezinskii et al 1990). In the leaky box model the cosmic rays oscillate rapidly in a fixed volume of the Galaxy, filling it uniformly, but slowly leak out of it via some unspecified mechanism. Diffusion models treat the propagation more realistically, and allow for leakage by assuming that at a certain height H in the halo the cosmic rays no longer diffuse but escape freely. This escape is then included in the diffusion equation by imposing the boundary condition that the number density N of cosmic rays vanishes at H.

These two standard types of propagation model give equivalent accounts of some cosmic ray properties, but lead to different results for others (such as the surviving fractions of radioactive cosmic rays). The two main differences between these types of models are in the spatial dependence of N and in the age distribution f of the cosmic rays. In the leaky box model f depends exponentially on the age, whereas in the diffusion models f contains a larger fraction of young particles because in these latter models the particles cannot escape until they are old enough to have diffused all the way to the height H.

Our trapping model has some points of similarity with the leaky box and the diffusion models. For example, the implied age distribution is exponential, as in the leaky box model. However, it is more realistic to assume in our trapping model that the cosmic rays propagate by diffusion, rather than by moving freely. This assumption leads to similar results as standard diffusion models for the spatial distribution of N (Ramaty 1974, Wallace 1980). For example in the trapping model it is clear that, for particles which are stable and lose negligible energy outside the clouds, N will become small at a height $\sim (Dt_0)^{1/2}$, where D is the diffusion coefficient and t_0 is the mean confinement time, since

few of these particles survive with an age exceeding t_0. This is similar to the boundary condition that N vanishes at H.

There are also important differences between the trapping model and the standard models. We describe three of these differences here.

1) In the standard diffusion models the height H where free escape occurs cannot be calculated a priori, since the magnetic configuration in the halo is unknown. Accordingly the mean escape time t_0, which $\sim H^2/D$ in these models, cannot be calculated either, even if the value of D is known. It must be derived from observations involving a cosmic ray clock, such as radioactive nuclei or the spectrum of high energy electrons (whose radiative losses provide a timescale).

On the other hand, in the trapping model t_0 is determined as $(\pi r^2 n v)^{-1}$, where r and n are the mean radius and number density of the clouds and v is the cosmic ray velocity. In the favoured model of the clouds $r \sim 10^{14}$ cm and $n \sim 30$ pc^{-3} (Sciama 1999), so that t_0 can be immediately derived as $10^{15} c/v$ secs.

2) The second difference concerns the dependence of H, D and t_0 on the cosmic ray energy E. In the standard models one assumes that H is essentially independent of E, being mainly determined by the magnetic configuration in the halo. On the other hand, D is found to depend on E in these models approximately as $E^{1/2}$ for relativistic nuclei, since their mean matter path length is observed to depend on E as $E^{-1/2}$.

By contrast, in the trapping model t_0 is independent of E for relativistic cosmic rays, and so the dependence of D on E here implies that H also depends on E (as $E^{1/2}$ for these rays, as is shown in section 3).

3) The third difference concerns the derivation of the value of t_0 from the observed abundances of the cosmic ray clocks. The leaky box model has an exponential age distribution, as does the trapping model, but leads to an underestimate of t_0 by its assumption that the short- lived clocks populate the same volume as their long-lived partners. On the other hand, the standard diffusion models lead to an overestimate of t_0 if the trapping model is correct, because they contain too many young particles in their age distribution. Accordingly, in the trapping model the value of t_0 derived from the observed abundances of the clocks must lie in between the values derived from the standard leaky box and diffusion models.

3 THE ENERGY DEPENDENCE OF $\mathbf{H, D}$ AND $\mathbf{t_0}$

For the discussion of this section we shall adopt a simple model in which the interstellar gas, of mean density ρ, is confined to a disc of height d (~ 300 pc), and that the thickness H of the halo (which contains a neglible gas density) $\gg d$. Cosmic ray nuclei originate in the disc, and during the mean time t_0 which they take to diffuse to the height H they return to the disc $\sim H/d$ times (Berezinskii et al 1990). Then the mean path length X for stable cosmic ray nuclei is given by $X \sim \frac{H}{d}\rho v \frac{d^2}{D}$, and so

$$\frac{H}{D} \sim \frac{X}{\mu v}, \tag{1}$$

where μ is the column density ρd, whose value is known (the contribution of dark matter molecular clouds not being included here). We also have $\frac{H^2}{D} \sim t_0$, so that

$$H \sim \frac{\mu}{X} v t_0 \tag{2}$$

and

$$D \sim \frac{\mu^2}{X^2} v^2 t_0.$$

It follows that H and D can be derived if X and t_0 can be measured (or t_0 derived from the trapping model). For $\mu \sim 5 \times 10^{-3}$ gm cm^{-2}, $X \sim 10$ gm cm^{-2} (for nuclei such as C with energy ~ 1 Gev / nucleon) and $t_0 \sim 10^{15}$ sec we obtain $H \sim 5$ kpc and $D \sim 2.5 \times 10^{29}$ cm^2 sec^{-1}.

We now consider the energy dependence of H, D and t_0. The observations show that, for relativistic nuclei such as C, $X \propto E^{-1/2}$ (Berezinskii et al 1990). In the standard models H is independent of E, and so (1) implies that $D \propto E^{1/2}$, which is a physically reasonable result. It then follows from (2) that in these models $t_0 \propto E^{-1/2}$.

By contrast, in the trapping model t_0 is independent of E for stable relativistic cosmic ray nuclei, and so in this case $D \propto E$ (which is still physically reasonable) and $H \propto E^{1/2}$, as was mentioned in section 2.

4 RADIOACTIVE COSMIC RAY CLOCKS AND THEIR MEAN CONFINEMENT TIME

The relative abundances of radioactive cosmic rays act as clocks which can be used to determine their mean confinement time t_0. The most recent data and analyses are due to Simpson & Connell (1998) and to Webber & Soutoul (1998). The latter data clearly show the influence of the time dilation of the decay lifetimes τ_0, which leads to $\tau = \tau_0 E/M_0 c^2$, but are

not yet accurate enough to test the energy dependence of t_0. One would also like to test the prediction of the trapping model that $t_0 \propto 1/v$ for nonrelativistic nuclei, but again the data are not yet sufficiently accurate.

One can, however, derive from the data reasonable numerical estimates of t_0 for the standard leaky box and diffusion models. Following Lukasiak et al (1994) and Webber & Soutoul (1998) one finds that at 1 GeV/nucleon these estimates are $\sim 10^7$ yrs and $2-3 \times 10^7$ yrs respectively. As discussed above, one would expect t_0 for the trapping model to lie between these values. Since this model gives, for relativistic nuclei, $t_0 \sim 10^{15}$ sec, we see that the model is in reasonable agreement with the data, as was already pointed out in paper I.

5 RADIATING COSMIC RAY ELECTRON CLOCKS AND THEIR MEAN CONFINEMENT TIME

It has long been recognised that high energy electrons, as well as radioactive nuclei, act as cosmic ray clocks. The reason is that these electrons lose energy, via synchrotron and inverse Compton radiation, at a rate proportional to the square of their energy. These radiative losses thus lead to ageing effects which increase with energy, and so can be discerned in the spectrum of the electrons. It is usually assumed that these electrons are produced by the same sources as cosmic ray protons and nuclei, and that they propagate through the Galaxy in a similar manner, except that allowance must

be made for their radiative losses. In these standard models the electrons escape from the Galaxy in the same way as the other cosmic rays.

In the dark matter molecular cloud model we need to consider what happens to an electron which enters a cloud. The most important effect is due to the bremsstrahlung radiated by the electron. It is known that, because of the resultant losses, the energy of the electron falls by a factor e when it passes through ~ 61 gm cm^{-2} of hydrogen (Ramana Murthy & Wolfendale 1993). Since this is close to the column density of a cloud in the favoured model, and since the energy spectrum of the electrons is steep ($\sim E^{-3}$ according to Tang 1984), it follows that an electron which enters a cloud is essentially lost to the interstellar distribution, just as is a cosmic ray nucleus. We would therefore expect a cosmic ray electron to possess the same confinement time as a cosmic ray nucleus also in this model.

It was recognised some time ago that the electron confinement time t_e must exceed its lifetime against synchrotron and Compton losses over a wide energy range. This recognition followed from two observational facts which demonstrate the radiative ageing of the electron population (Webster 1978). This first of these facts is that, at every frequency at which a comparison has been possible, the radio halo of the Galaxy has a spectrum which is steeper than that of the disc. Secondly, the scale height of the radio halo decreases with frequency (as it does for other galaxies, e.g. NGC 891 (Allen et al 1978) and NGC 4631 (Ekers & Sancisi 1977). This effect is attributed to the fact that the lower energy electrons travel further in their longer radiative lifetimes (Ginzburg 1953).

Since a typical radiative loss time, for say a 30 GeV electron, $\sim 10^7$ yrs (Ramana Murthy & Wolfendale 1993), we would expect that $t_e > 10^7$ yrs, in agreement with the estimate of t_e in section 4. A somewhat more precise result for t_e has been obtained by Tang (1984) on the basis of his observations of the cosmic ray electron spectrum for energies between 5 and 300 GeV. He found that $dN/dE \sim E^{-2.7}$ around 10 GeV and $\sim e^{-3.5}$ around 40 GeV. This spectrum is different from that of cosmic ray protons, which $\sim E^{-2.65}$ above 10 GeV. Tang interpreted the steepening of the electron spectrum in terms of radiative energy losses by the electrons.

His analysis was based on the assumption that the observed spectrum represents the competing processes of radiative energy losses in the interstellar medium and leakage out of the Galaxy. He conducted this analysis in terms of both the leaky box and the diffusion models. If one combines his two best fits to the electron energy spectrum one finds for the leaky box model $t_e \sim 1.5 \times 10^7$ yrs, and for the diffusion model $t_e \sim 2.5 \times 10^7$ yrs. According to our discussion in section 2 we would expect that in our trapping model t_e would lie between these two values, say $t_e \sim 2 \times 10^7$ yrs. This result agrees well with the values derived from both the observed abundances of radioactive cosmic rays and directly from the favoured cloud model.

6 THE AGE DISTRIBUTION OF COSMIC RAY ELECTRONS AND THE ENERGY DEPENDENCE OF t_e

We now consider the constraints that can be imposed on the age distribution of cosmic ray electrons and on the energy dependence of their mean confinement time t_e from observations of the electron spectrum at high energies. The influence of the age distribution was examined by Ramaty & Lingenfelter (1971) and of energy dependent escape by Silverberg & Ramaty (1973) (see also Ramaty 1974 and Ormes & Freier 1978). Particular stress was laid on the sensitivity of the electron spectrum to the relative number of young electrons by Giler et al (1978).

Purely for convenience of exposition we shall regard the exponential age distribution as the fiducial one, from which a number of variations can be contemplated for different reasons. As we have seen, the standard diffusion models lead to an increase in the relative number of young particles, the effect of which would clearly be to flatten the electron spectrum at high energies. There are also models in which there are relatively fewer young particles than in the fiducial distribution. These models were introduced because of observational data on the relative abundances of spallation products of medium and heavy cosmic ray nuclei (Garcia-Munoz et al 1987). These data suggested that the cosmic ray path length distribution may be truncated at low path lengths to an extent which decreases with energy. This effect has been controversial. If it is real and is due to excess matter surrounding the cosmic ray sources, then it would not affect the age distribution of the cosmic rays. If, however, the effect is due to a paucity of nearby cosmic ray sources (Cowsik & Lee 1979) then there would also be a truncation in the age distribution at low ages. This truncation would steepen the electron spectrum at high energies, as discussed in particular by Giler et al (1978), Tang (1984) and Webber (1993).

Similarly, if the mean confinement time t_e decreases with energy, say as $E^{-1/2}$ as in diffusion models, then this would act in the same as an excess of young particles, and would flatten the electron spectrum at high energies, as discussed by Tang (1984).

We are now in a position to consider the analyses which have been carried out of the observed electron spectrum by various authors (Giler et al 1978, Prince 1979, Protheroe & Wolfendale 1980, Nishimura et al 1980, Tang 1984, Webber 1993). The most recent of these analyses are due to Tang (who used his own data which extend out to 300 GeV) and to Webber (who used both Tang's data and also those of Nishimura et al (1980) which extend out to 2000 GeV). The difference in these data is important because the Nishimura et al spectrum is significantly flatter than Tang's, and this difference affects the range of acceptable models.

The analyses show that the standard diffusion model, with its excess number of young electrons and its energy dependent t_e, leads to a flatter spectrum than even the Nishimura et al one, and so perhaps can be ruled out. Models with a truncation in the age distribution at high energies

could rectify this disagreement, but would probably be inconsistent with the path length data at high energies.

On the other hand, our trapping model, with its exponential age distribution and energy independent t_e would fit the Tang spectrum, but not Nishimura et al's, which is too flat. To resolve this problem we need further data at high electron energies.

7 CONCLUSIONS

In this paper we have pointed out that, if the dark matter in the Galaxy consists of molecular clouds, if cosmic ray electrons can penetrate these clouds, and if this penetration rather than escape from the halo determines their confinement time, then consistency with Tang's (1984) observations of the high energy electron spectrum would be achieved. The agreement with observation involved applies to the mean age t_e of the electrons, to the independence of t_e from the electron energy, and to their (exponential) age distribution. On the other hand, if Nishimura et al's (1980) earlier and conflicting observations are correct, our trapping model can be ruled out.

By contrast, the simplest versions of the leaky box and diffusion models, all of which assume that the electrons escape from the boundaries of the halo, are contradicted by both sets of observations.

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